Very large Optics for the study of Extrasolar Terrestrial Planets
Report on Phase I work achieved to May 31st 1999

Introduction

Our Phase 1 study for the design and production of very large optics for the study of extrasolar planets followed an analysis that advanced spectroscopic studies of terrestrial planets will need four ~25m class telescopes, and that minimal imaging will require 25 100m class telescopes. We recognized this in our Phase 1 proposal. This discussed a particular way of making 100m ultralightweight telescopes.

Since then NASA has also recognized the need for the development of ultralightweight optics. In order to prepare for work in this area, a conference on ultra lightweight optics was organized by Richard Capps of JPL and it was held at Napa in March 1999. Our group presented five of the papers at this meeting, as a result of our phase 1 NIAC award.

The present state of the art in very lightweight optics as described by Marshall Spaceflight Center was reported at this meeting (Catanzaro, Crowe and Kasi 1999). That state of the art is the demonstration optics for NGST developed by our group a few years ago. The same paper shows a goal of 5Kg/m2 optics by the year 2010, and shows a question mark on how that might be achieved. The 53 cm demonstration of 20Kg/m2 optics is shown as figure 1a, and the performance of the optics is shown in figure 1b.

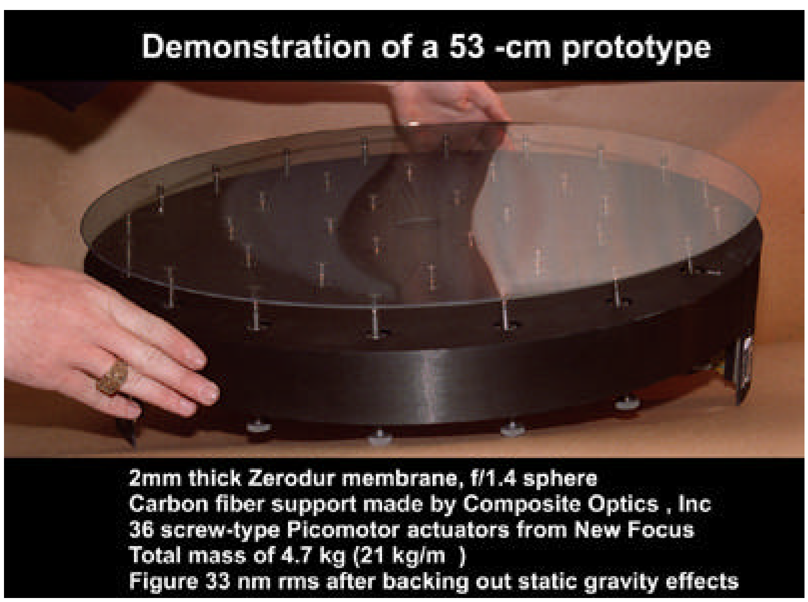

Figure 1a. The 53 cm NGST demonstration optics at 20Kg/m2

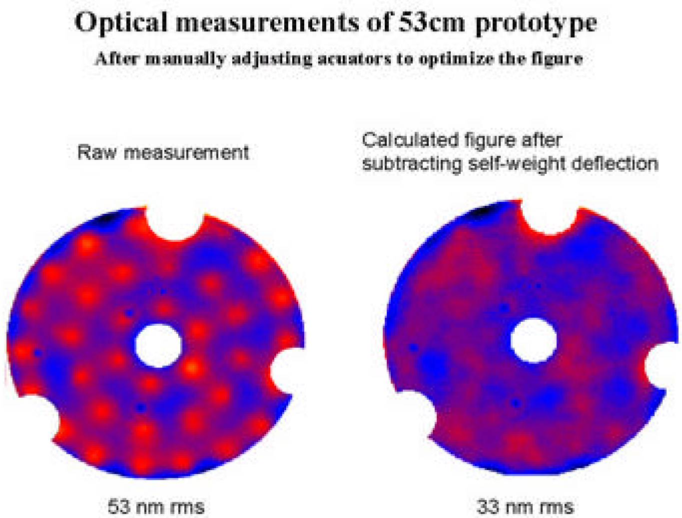

Figure 1b. Optical performance of the NGST demonstration

The telescope concept (extracted from Phase I proposal)

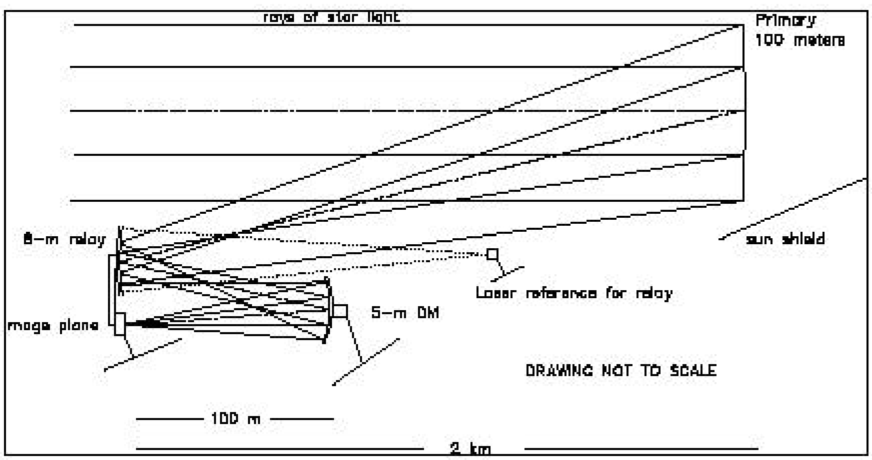

Figure 2a The sketch for a 100m telescope using flat hexagonal segments shaped as a large paraboloid mirror.

Although the study of extrasolar planets will require huge apertures, there are some features of observations of the planets that mitigate these difficulties. The planet is accompanied by a bright star, which can serve as a useful wavefront reference. And the field of view is tiny needed to observe complete extra-solar systems will in general be far less than 1 arcsec, so that non-isoplanatic effects will be very small.

An aperture of about a hundred meters across of low mass will require some sort of adaptive correction to maintain high quality in the face of thermal and other perturbations. We propose making the telescope in three separately flying stages **B**an *objective*, like a primary mirror or objective lens, a *collector* and a tertiary *corrector* or deformable mirror. The concept is shown schematically in figures 2a and 2b.

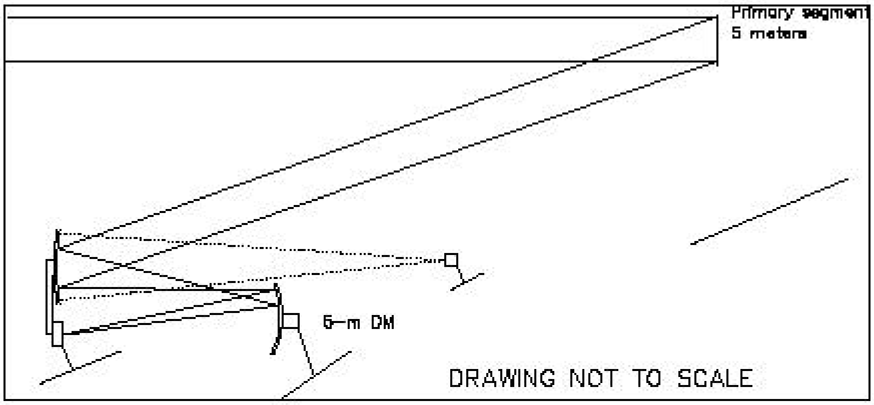

Figure 2b. The light path from a single flat segment

The first stage is the *objective,* which is a focusing element that corrals the light and directs it toward the much smaller collector. It is optimized to be as large as practical while having low enough mass to be launched. It directs light into the collector, which itself may be many meters across. It is made up of many segments, which in our concept are flat. Thus the objective would look like a paraboloid on the large scale, but would have departures on the small scale because it would be approximated by flats segments.

The *collector* is a spherical or paraboloid mirror many meters across that images the objective onto the tertiary corrector or deformable mirror (DM). Its shape would be measured in situ using a laser interferometer at the center of curvature, and controlled via actuators.

The *corrector*, which also may be many meters across, is a nominally spherical mirror which has small segments, each one corresponding to a flat segment in the objective. Each segment has built in curvature to compensate for the missing curvature of the flat segments of the objective. In addition, the individual segment shapes would be distorted under computer control to compensate for errors in flatness of each objective segment. The actuation of the corrector elements in the manner of a deformable mirror can be made by extending the technologies developed for ground based deformable mirrors, for lower mass and lower frequency operation. The actuation would be similar to that the University of Arizona is building for an NGST prototype.

The new concept makes a radiacal departure by making the primary mirror of flat segments. This takes advantage of the space environment where flat segments are the natural shape achieved with gossamer thin material placed under tension. Large flat elements can be made by stretching the material between points in a plane, provided the material is uniformly thick. Even penetration by micrometeroids etc. will not change the flat shape!

If the membrane is to be a regular polygon, we need tensioning elements (force actuators or springs) at each corner, adjusted under active control to achieve co-planarity. The active servo control is from wavefront measures, and is updated to counter the thermal or other distortions of the support frame. We deliberately define the perimeter by discrete points, with the membrane otherwise unsupported, because the unsupported edge will naturally be straight from point to point and will not have a long-scale departure from co-planarity. One of the goals of phase 1 was to explore the construction of optical surfaces with stretched plastic membrane.

The Collector and DM (Corrector)

The collector and corrector mirrors would be made using the advanced rigid lightweight mirror MARS concept being developed at the University of Arizona for the Next Generation Space Telescope (NGST). But these curved optics would be too heavy if made at the same density as the NGST optics (15 kg/m^2). Therefore we have seen an additional necessary goal for Phase 1 to identify the way of making these optics at lower density. We have studied in Phase I ways to push the basic concept of using an actively supported membrane for NGST design from the NGST value of 15 kg/m^2, to less than 5 kg/m^2. This would enable the use of 8-m mirrors that weigh only 250 kg. For comparison, current ground and space telescopes operate with typical surface densities of 600 kg/m^2. We envisage the demonstration of 5 kg/m^2 optics by the year 2002, rather than the goal set by Marshall SFC for 2010.

We note that if we could solve the problem of making the collector and DM needed as auxiliary mirrors for the flat segmented objective concept, these mirrors would in their own right make a telescope adequate for the next phase of exo-planet spectroscopy beyond TPF. As is the case for NGST, these mirrors are larger than available or proposed launch vehicles and will need to be made from segments that get deployed into place on orbit.

Membrane and Rigid Structure (MARS) concept

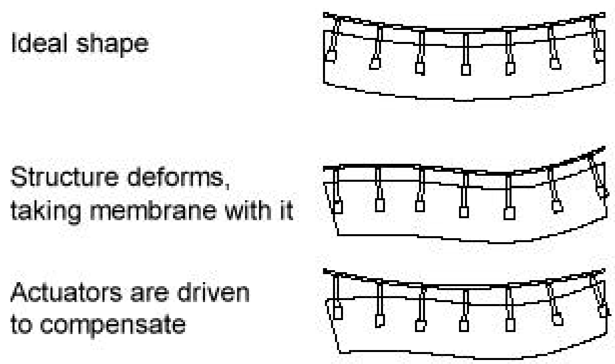

Figure 3. The concept for ultralightweight curved optics from Phase 1 proposal.

c) Advanced Concept Work Plan

We planned the preliminary 6-month study phase to be almost exclusively analytic. However we noted that Awhen suitably small experiments arise within the framework of the study resources we would conduct them. We do have the manufacturing and measuring resources of Steward Observatory Mirror Lab available. In the past, we have e.g. conducted experiments on the manufacture of 2mm thick glass shells of 20cm diameter within such constraints. In fact we found such development unnecessary with glass, but necessary with actuators.

Achievements under the contract

In our work under this contract, five papers have been presented at the Ultra Light Space Optics Challenge as described in the introduction. The conference papers are available at http://origins.jpl.nasa.gov/meetings/ulsoc/presentations.html. These papers are given as Appendix 1-5. There are also unpublished results of our phase 1 work which are also reported here.

Thin mirror analysis: We first analyzed the mechanical behavior of thin mirrors on a bed of actuators (Burge and Cuerden 1999 – appendix 1). Membrane mirrors on a finite number of supports are limited by actuator print through into the mirror figure. Using triangular load spreaders can reduce the print through by a factor 9.

Low surface density: We also showed how we can achieve 5Kg/m2 surface density (Burge, Angel, Cuerden and Woolf 1999 – appendix 2) using thin glass technology. Part of the new requirements for making these mirrors and their support systems are for nanometer actuators of extremely low mass.

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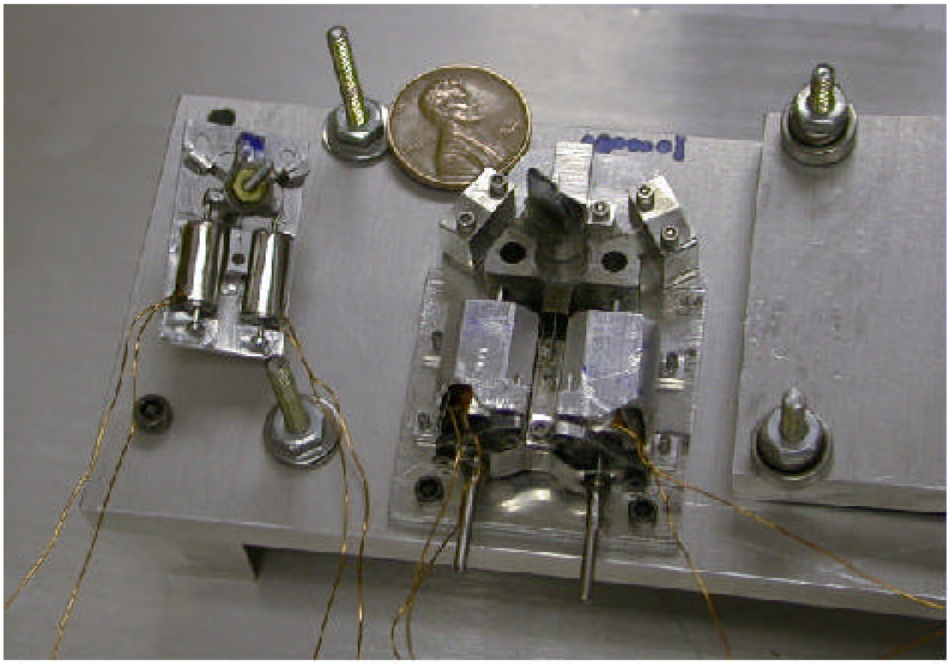
Figure 4 The 7g actuator shown alongside the 37g actuator for NGST



Low mass nanometer actuators: We have developed prototypes for 7gram actuators under this contract (Cuerden and Angel 1999, also as Appendix 3

Composite thin reflectors: We have felt it important to use the opportunity of having the same very low mass support structure to explore an alternative technology for faceplates. We may be able to make the mirror surfaces at about 1/3 of the mass of the glass, and allow surface densities of ~3Kg/m2 to be achieved. This is with composite surfaces, and our team has acquired a sample mirror substrate as part of the work under this contract (Hoffmann, Woida, Burge and Catanzaro 1999- appendix 4). The work included design, fabrication, performance analysis, and delivery of a thin composite mirror shell by Composite Optics. This has a diameter of 0.5-meter, thickness of .46 mm, and concave spherical surface of 7.5-meter radius of curvature, and areal density less than 1.25 kg/m2. We had hoped to include optical testing of this sample under phase 1 of the contract, but it was not possible and it is deferred for phase 2. It may be that the lower surface density is only appropriate for longer wavelength observations than is the glass, which seems adequate for use right through the visible region into the UV, but there would be a useful niche for the technique even should that be the case.

Figure 5 The 50cm composite shell showing an oblique reflection.

Figure 6 The composite shell on the NGST demonstration support

Flat Plastic Hexagons: A principal goal is to be able to make large extremely lightweight hexagons of metallized plastic that can serve as the 100m diameter reflectors that would be useful either for imaging, or as an alternate way of performing spectroscopy. Our work as of two months ago under this contract was summarized (Angel, Burge and Woolf 1999). Since then we have made four ~ 1m hexagons of stretched plastic, to explore means of stretching the material, and to help understand the difficulties. There have also been theoretical studies by our engineer Warren Davison to show us the issues involved in creating a flat stretched plastic film. The key need is to have a positive tension in two orthogonal directions. We are exploring various means of holding the plastic near its edge to achieve this over as much of the surface as possible. Our last hexagon is shown in the picture underneath where NASA director Mr. Goldin is seen holding it .

Figure 6. Plastic hexagon and support structure held by Mr. Goldin

Figure 7 The first stretched plastic mirror

Prototype flat plastic test results

We made a number of trials of stretched plastic, including both aluminized mylar, and polyimide. We tried stretching the plastic both with frames that gripped it along the edge, and with attachment to points.

As part of our phase 1 study, we constructed gossamer flat hexagonal mirrors with 50cm between thse support points.   The hexagon in the final version was from 12micron thick polyimide made by SBS of Huntsville Alabama. It is replicated from solution off float glass, a process that could be extended to 8m aperture, on an 8m flat from the Mirror Lab.

The 6 corners are gripped by 2.5cm wide clamps, where tension of 20N is applied in the plane by a spring. The tensioning system is made from 6 carbon-fiber composite arrow shafts.projecting radially from a hub. The Z axis adjustment is made with wires and screws at the bottom end of the hub (see the figure in the phase 1 report). Note that the membrane tensioning and position actuators have no cross coupling. The total weight of this prototype including membrane, grips, springs, arrow shafts and center hub is 0.4Kg. Prelimiary optical testing was performed with a test sphere of 10m radius of curvature. The best spot shown in phase 1 report is 2mm diameter. This corresponds to a suface slope of 40 micro radians or 10 arc seconds. Inspection of a knife edge at the image shows the main residual error is still low order. There is no evidence of stretch creases emanating from the supports. The adjustment is limited by the coarseness of the 0-80 adjustment screws. Detailed precision testing is deferred until phase 2.

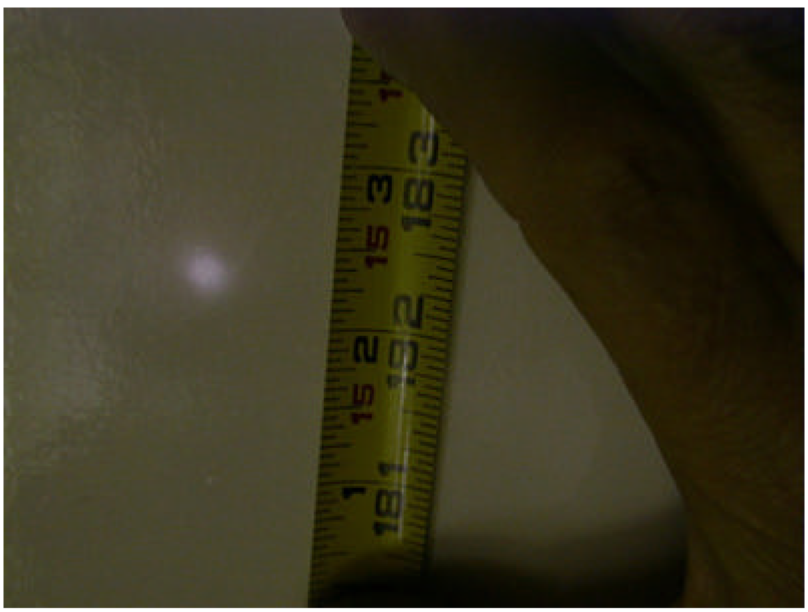


Figure 8. Observation of image spot size in autocollimation from the stretched polyimide.

Additional Unpublished Studies

Thermal Shields

During these studies it became apparent that a major factor not considered for these telescopes is the mass of a thermal shield. For example, the NGST current heat shield design has a surface density referred back upon the primary of ~3Kg/m2. And the concept discussed for TPF is even more massive. Thus without a substantial reduction in heat shield mass, the benefits of large ultra-lightweight optics would be lost.

At the same time, there are dynamical issues if we choose to make the free-flying parts of our telescope operate at substantially different radial distances from the Sun. For both of these reasons, we are proposing that the telescope observations be restricted to those that are nearlytangent to the sphere around the Sun, and with the telescope at its surface. Then the opticalcomponents are nearly edge-on to the Sun, and can operate with reduced area shields.If the telescope is permitted to deviate from the tangent direction by +/- 10 degrees, then for worst case objects, 40 days of observing per year are possible. Such a range should permit small heat shields.

Telescope Dynamics

The parts of the telescope will be separated by as much as 2Km. and be free-flying units. With as much as a 10 degree deviation from the tangent line, the components may be separated by as much as ~300m in the direction towards the Sun, or $2x10^{-6}$ of the radial distance. Thus there will be a small acceleration of rate ~6 10^{-7} g. required by the lowest mass part of the equipment for it to keep step with the rest of the telescope. This seems relatively easy to achieve

Telescope Optical Performance

We have performed a zero order analysis of the limitations that our telescope design will cause. First there will be a vignetting of images that extend by more than 1-2 arc minutes. Secondly, the demagnification onto the deformable mirror causes off axis angles to grow by the magnification factor. As a result there is a phase error that grows with angle, and becomes a significant fraction of a wavelength for off axis angles of >1 arc minute. Fortunately the resolving power of a 100m telescope is such that this limitation will not be important for the uses considered here.

Potential Space Test of Stretched Plastic

A rapid test of a flat in space would be extremely useful demonstration. It could be made by reflecting starlight from a 2.5m flat into the Hubble SpaceTelescope. This test could be made after the 2003 servicing mission. The flat could be carried aboard the shuttle, and placed in orbit beside the telescope, at a distance of a few hundred meters. When the telescope was again operating, it would be pointed at the flat to observe the reflected starlight.

We have developed a concept for such a test, which is described in our Phase 2 proposal. For this work, and with the assistance of Lockheed Martin we have developed a concept for a free-flying flat, shown in figure 9.

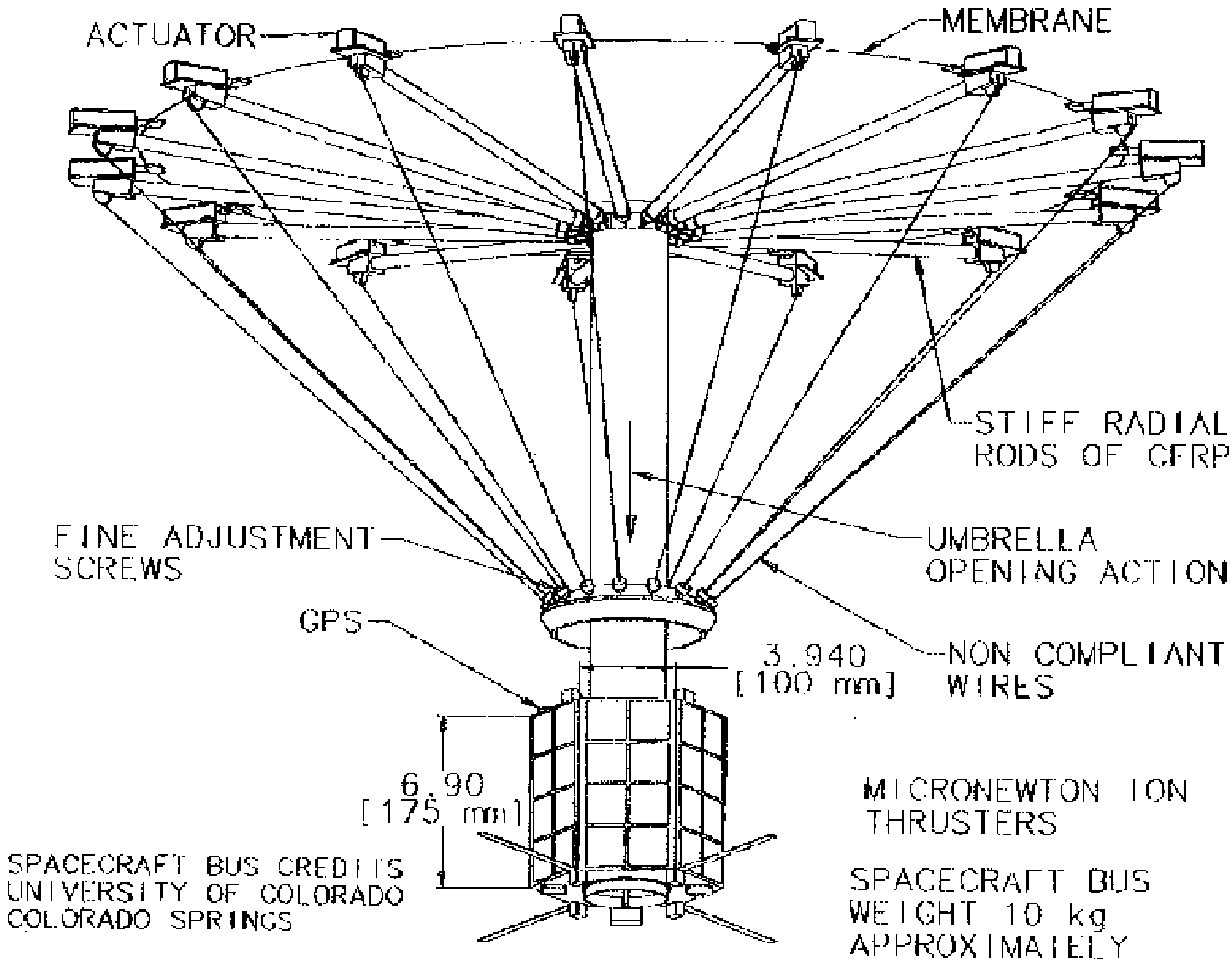


Figure 9 Flat plastic and bus concept for a space test

Conclusion

The results of Phase 1 show that very large telescopes of low mass in space appear possible. The real issues of making very large telescopes of this type require small scale hardware tests, and these are proposed for phase 2.

References

Capps R 1999 (Editor) Ultralightweight Optics Conference
http://origins.jpl.nasa.gov/meetings/ulsoc/presentations.html.